A Dual-low-frequency Radar for Sub-canopy and Deep Soil-moisture Measurements

Delwyn Moller, Ernesto Rodriguez, Mahta Moghadamm and James Hoffman
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91107
818 354-9780
delwyn.moller@jpl.nasa.gov

Abstract—Measurements of deep and sub-canopy soil moisture are critical in understanding the global water and carbon energy cycle, but are not presently available on a synoptic basis. In this paper, we discuss a proposed spaceborne dual-frequency (UHF and VHF) radar that can provide globally these key measurements. This system is polarimetric and the low transmit frequencies chosen for their penetration abilities necessitate a large antenna that has an aperture of approximately 30m by 11m at VHF, and 30m by 3m at UHF. We describe the mission concept, overall system design and performance characteristics, and discuss ongoing tasks to prototype key system components, and verify the retrieval algorithms.

We are also developing a tower-based prototype radar system. This system will, through field observations, demonstrate the scientific effectiveness of the measurement concept and provide critical data for algorithm development. We provide details of the ground experimentation including issues unique to operating at the low-frequencies chosen for these systems.

TABLE OF CONTENTS

1. INTRODUCTION

Simultaneous estimation of deep (order 0.1 to 1 m) and shallow (order 0.01 to 0.1 m) soil moisture at spatial resolutions on the order of 1 km could provide a major breakthrough for estimation of vertical flow in the soil column linking surface hydrologic processes with that in the subsurface. The key controlling variable of the hydrologic partitioning over terrestrial surfaces is soil moisture and its profile within the root-zone. Surface moisture and its variation are controlled by surface soil evaporation and runoff. Deeper moisture and its variation are strongly related to drainage and transpiration by deep-rooted grasses and trees. The difference between the two reservoirs characterizes the soil moisture gradient, which undergoes frequent reversals in response to wetting and drying periods. Measurements with repeat intervals corresponding to storm and interstorm intervals (~3-7 days) allow adequate sampling of the moisture gradient dynamics, which in turn allows the estimation of fluxes. This science data product distinguishes the measurement set proposed here from that of any other existing, planned, or proposed mission.

To penetrate vegetation, soil surface, and deep soil, lower-frequency microwaves are needed due to their ability to travel through significant vegetation canopies and through soil without losing needed information content. Although passive microwaves have been widely used in several past, present, and planned radiometer systems, they are best for retrieving surface soil moisture in no- or low-vegetation areas [1,2,3]. In the presence of vegetation and to penetrate into deeper soil, a radar is needed to achieve the required resolutions at lower frequencies with reasonable antenna sizes. The radar systems described in this paper address this need as the Microwave Observatory of Subcanopy and At-depth Subsurface (MOSS) program.

In this paper Section 2 describes the MOSS mission concept discussion temporal and spatial sampling requirements, revisit time and orbit choice and frequency allocation issues. Section 3 presents the instrument parameters and shows simulated predictions of performance. Section 4 introduces the tower-based radar, discussing the implementation and experimental plans for this system that will be used for algorithmic development and verification. Conclusions are drawn in Section 5.

[1] IEEEAC paper #1230, Updated October 17, 2002

2. MISSION CONCEPT

For MOSS two observation frequencies will be employed: 435MHz P-band or ultra-high frequency (UHF), and 137MHz very-high frequency (VHF). P-band measurements are needed to characterize vegetation effects [4, 5, 6] and retrieve soil moisture in the 0cm to 50cm depth, depending on the amount of soil moisture present [7]. VHF data are used for retrieving moisture under vegetation canopies exceeding 20 kg/m^2 and to depths of 2m or more, depending on the amount of moisture present. However, at least one of the higher frequencies, preferably P-band, must be present for separating, characterizing, and removing the contribution of the vegetation layer. Ideally additional higher frequency (L-band) measurements would be used to estimate surface soil moisture [8, 9] but as these capabilities are addressed by other concurrent programs this will not be a component of MOSS with the exception of the tower-based radar which will take L-band data for comparative purposes during algorithm development.

Requirements

To characterize the canopy requires fully polarimetric measurements as does removal of ionospheric effects [10, 8]. Furthermore, to insure proper sampling of the surface and subsurface moisture by achieving adequate penetration depths into vegetation and soil, small incidence angles are needed. Our model simulations have shown that incidence angles in the range of 15 to 35 degrees would satisfy this requirement. The sampling requirements are a key factor driving the system and mission design. For soil moisture at depths of the order of 1 meter or more, the requirements are different and a repeat observation time of 7-10 days is reasonable to capture variations of the deep soil moisture.

To meet the temporal coverage requirement, a large (300-400km) swath is required, while meeting the requirement that the incidence angle be small and vary moderately over the swath implies that the platform altitude must be large enough so that a relatively small range beam-width fully covers the entire swath. To meet these requirements, we choose an orbit with an altitude of 1313 km, which results in a range of incidence angles which vary between 17 and 32 degrees. To achieve these beam-widths, the width of the VHF aperture must be 11 m, while the width of the UHF aperture must be 3 m. Smaller apertures could be used if ScanSAR data acquisition were possible, but due to the size of the antenna and the frequency separation of the signals, a center-fed reflector antenna is desirable, making scanning of the beams undesirable.

The resolution requirement of O(1km) is consistent with the majority of regional scale process models and is sufficient to capture surface variations within coarser resolution grids for continental and global models. This also makes the scale of soil moisture measurements compatible with vegetation parameters derived from spaceborne instruments such as AVHRR and MODIS.

Additional constraints on the system design are levied by the requirement that both range and azimuth ambiguities be minimized, while keeping the average instrument power and data rate to a minimum. Average instrument power, data rate, and range ambiguities can be reduced by utilizing a low pulse repetition frequency (PRF). This leads to a requirement that the antenna width be approximately 30 m, assuming that only part of the azimuth bandwidth is processed, to avoid azimuth ambiguities. Although to achieve full SAR resolution with quad-pol operation an antenna length about twice this long is needed, the science requirements on resolution are relaxed enough not to mandate such antenna length.

Antenna Implementation

The simultaneous requirements for 30 m antenna length and antenna widths of 3 and 11m for UHF and VHF requires a mechanical implementation which can only be practically deployed in space if the antenna aperture is shared by both of the frequencies under consideration. An efficient method for sharing the apertures for the bandwidths required by our design is to use a reflector antenna, which theoretically has infinite bandwidth. From a practical point of view, light reflector antennas have recently been demonstrated with apertures as large as 12m [11, 12]. Consequently, as illustrated by concept in Figure 1, a parabolic reflector antenna center-fed by a linear array feed is the antenna implementation identified as the most suitable for this application. The design and feasibility of such an antenna is a key technology driver for this design and is the subject of current efforts to support this concept. As part of this program a scale-model prototype of the feed will be built and tested [13].

Ionospheric Effects

To minimize the effects of ionospheric fluctuations and optimize local sampling times for soil moisture, it is desirable that a sunrise/sunset sun-synchronous orbit be selected. These and other requirements discussed previously lead to the choice of a sun synchronous 6am-6pm orbit with a 1313 km altitude, an inclination of 101 degrees, and a repeat period of 8.7 days.

.Frequency Allocation

A persistent concern with operating a radar at low frequencies is the frequency allocation limitations imposed by the Federal Communications Commission (FCC). Most of the electromagnetic spectrum in the 100 MHz to 1 GHz range is currently allocated for military or civilian applications such as television, radio, and mobile communications. In order to maximize the likelihood of gaining frequency allocation we have constrained the system bandiwidth to just 1MHz at both VHF and UHF. To address the allocation issues a detailed spectrum analysis was performed by an independent contractor in support of a stage 1 submission to the NTIA. The results of thes analyses suggest that a primary allocation already exists at VHF at 137-138 MHz and the report recommends that a Stage 1 approval be granted for this band. At P-Band 435MHz has been recommended for Stage 1 approval given there is strong national and international support for a SAR system within this band.

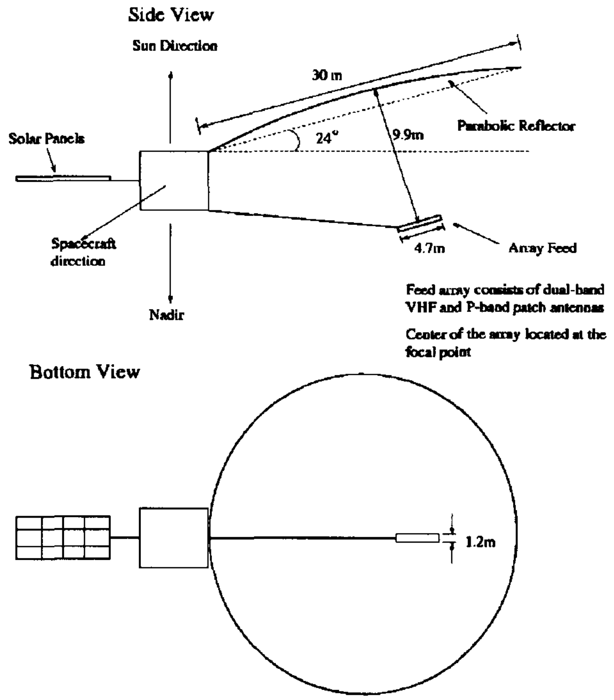

Figure 1: Mission configuration of antenna and spacecraft

3. Instrument Design and Performance

A preliminary design for a radar system capable of simultaneously meeting all of the measurement requirements mentioned above has been completed. The system parameters are summarized in Table 1. The pulse repetition frequency (PRF) was maximized to lower the azimuth ambiguities to a reasonable level but is still low enough to achieve a swathwidth that fulfills the revisit time requirements. A long (140us) pulselength is used for both systems enabling a relatively low transmit power of 2kW. The data rate of 1.7Mbps assumes block floating point quantization or approximately 4bits/sample and does not take into account the duty cycle of land/ocean time of the orbit.

To assess the performance of the proposed system, an echo simulator was written that incorporates a "rough-surface Bragg" soil σ_0 model [14],[15]. Also incorporated are modeled E- and H-plane antenna patterns at both frequencies that take into account the effects of blockage and enable us to calculate the azimuth and range ambiguities. The cross-polarizing properties of scenes have not been simulated at this point.

Figures 2 and 3 show some results from these simulations for P-band and VHF respectively. In these figures the upper panel shows the predicted H-polarized performance and the lower panel shows the predicted V-polarized performance. Please note that in these figures the green line is simply a reference that indicates the timing of the transmit pulses relative to the echos but is not adjusted in any way to match the power levels on the graph. Also, the range-ambiguity levels are not plotted since the relative levels are very low (<-60dB).

Considering Figure 2, for a given pulse, the data-swath begins approximately 8.9-9.8ms after the transmitted pulse as depicted by the black line. Note that the distinctive ripples in the return are due to ripples in the UHF antenna pattern and are a result of the feed array implementation. Ultimately these ripples will be thoroughly characterized and corrected for in calibration. For this system we interleave vertically and horizontally polarized pulses, and therefore the rolloff from these returns into adjacent inter-pulse-periods are a source of cross-polarized ambiguities; these are depicted by the red line. The azimuth ambiguities for UHF are –20dB with respect to the signal return as shown by the blue trace. The magenta trace shows the thermal noise level relative to the echo strength. Although the SNR is often at or below zero, the number of looks ranges from 53 (at near-range) to 102 (at far-range), ultimately providing acceptable performance as will be illustrated subsequently.

Parameter	UHF	VHF
Altitude	1313 km	1313 km
Swath Width	346 km	346 km
Antenna Width	2.8m	11m
Antenna Length	30m	30m
Center Frequency	435 MHz	137 MHz
Bandwidth	1 MHz	1 MHz
No.Looks/1km (min.)	54	40
Peak Power (1 channel)	2kW	2 kW
Pulse Length	140usec	140usec
Duty Cycle (2 channel)	13%	13%
Avg. Power (2 channel)	255W	255W
PRF (1 channel)	455Hz	455Hz
Processing Bandwidth	137Hz	182Hz
Noise Equivalent Sigma0	-18dB	-30dB
Data Rate (dual channel)	1.7Mbps	1.7Mbps
Incidence Angle Range	16-32	16-32
Azimuth Ambiguities	-18dB	-20dB

Table 1: System design parameters

Figure 3 shows the predicted echos for the VHF radar. The broader antenna pattern at this frequency has constrained the processing bandwidth to just 30% of the PRF and the result is azimuth ambiguities –18dB from the signal. Again the SNR is somewhat low but ultimately offset by 40 looks in the near-range to 78 looks in the far-range.

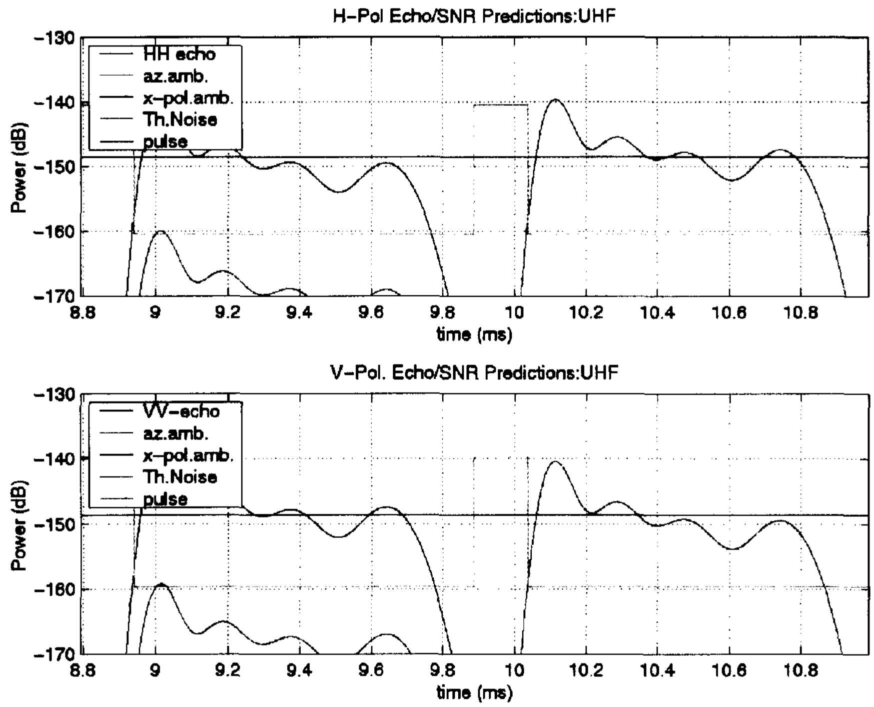

Figure 2: Simulated echo profile and cross-pol. and azimuth ambiguities for UHF radar

Figure 4 shows how the swath is determined for both VHF and P-Band. The swath is determined based upon several factors:

1. The swath is constrained within the inter-pulse period (IPP).
2. The cross-polarization ambiguity must be at least 20dB below the signal.
3. The sensitivity (or relative calibration) shall be less than +/-1dB.

The sensitivity is calculated as:

$$\Delta P = 10\log_{10}(P_s) - 10\log_{10}(P_s - \sigma)$$
$$= -10\log_{10}\left(1 - \frac{\sigma}{P_s}\right)$$

where P_s is the signal power, and σ is the standard deviation of the received signal. It can be shown that:

$$\frac{\sigma}{P_s} = \frac{1}{\sqrt{N}}\sqrt{(1+\frac{1}{SNR})^2 + (\frac{1}{SNR})^2} \qquad (1)$$

where N is the number of looks [16]. Using the above constraints, figure 4 shows that at both frequencies the swathwidth encompasses almost the entire IPP. The result is a swathwidth of 346km with an incidence angle range 15.7-31.7 degrees. Also of note is that the sensitivity is not the limiting constraint and so in both instances the performance exceeds the requirement.

4. TOWER-BASED PROTOTYPE.

To validate the MOSS concept, we will conduct a ground campaign whereby radar data at P-band and VHF will be collected coincident with L-band data at Co-I instrumented test sites. Although the low system frequency and the tower installation make this implementation cumbersome, because the scene itself is relatively static the measurements may be taken sequentially and a single acquisition can extend up to an hour without appreciable changes occurring at most scenes.

Field Operations

The radar itself will be a simple pulsed system utilizing, for the most part, readily available off-the-shelf components. The transmit source sequentially generates VHF, P- and L-band signals which are transmitted using one set of broad-band log-periodic antennas. These antennas have extremely broad beamwidths and so both vertical and horizontal arraying is required to constrain the field of view. To achieve this the antenna set is mounted on a 45m high tower-trailer (see Figures 5 and 6) and moved vertically on

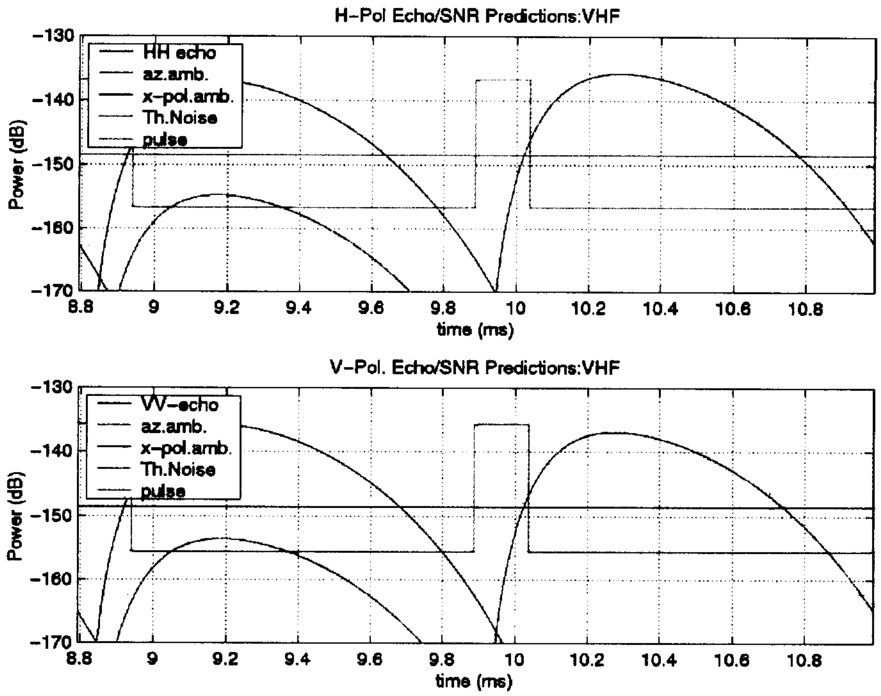

Figure 3: VHF echo predictions and azimuth and cross. pol. ambiguities

the retractable tower to synthesize a 10m vertical array thereby restricting the incidence angles to a scientifically useful range. The tower is also towed along-track by random spacings, some small enough to approximate one-half the L-Band antenna width, and over an extent of approximately 10m to synthesize an aperture in that dimension. Using both horizontal and vertical aperture synthesis (through tower retraction and translation) the

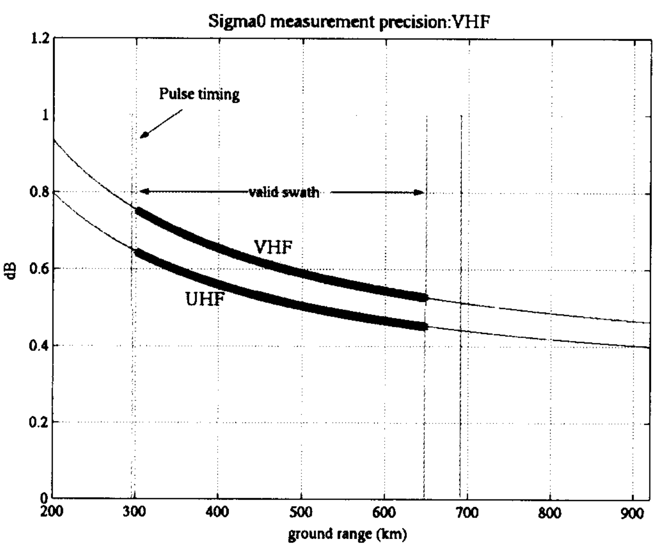

Figure 3: Swath determination within IPP

backscattered returns are from an area approximately 15m in azimuth x 10m in range.

The antennas are crossed for horizontal polarization (H-pol) vertical polarization (V-pol) sensitivity. A switching network enables switching between the V- and H-polarized transmit and receive antennas allowing for a fully polarimetric collection. To obtain independent samples we will move the tower-based antenna structure horizontally (in addition to that required for aperture synthesis) in addition to sub-banding the 30MHz transmit bandwidth into 1MHz bins.

Radar System Design

Figure 7 shows a system diagram of the tower radar. A frequency generator is used to produce all three transmit frequencies in sequence. The transmit signal is routed through a switching network to either the V- or H-pol antennas. The transmit/receive switches (fast switches) switch at 30ns yielding ~30MHz bandwidth. There is a single receive path and the received signal is filtered by the appropriate filter in the bank. The received signal is then mixed to baseband, and sampled in-phase and quadrature. The data are then stored on a PC for in-field and post analysis. The network of switches that determine the transmit and receive paths are used to sequentially select all four polarization combinations (VV VH HV HH) at all three transmit frequencies.

Data Processing and Field Evaluation

The goal of the MOSS processor is to increase the ground and subsurface spatial resolution by forming a synthetic aperture through the coherent combination of returns obtained by collecting data in a two-dimensional grid. Challenges in the focusing and estimation of the radar cross section are presented by the wide band nature of the radar signal; by the knowledge requirement for the antenna position; and by the presence of radio frequency interference (RFI) at UHF and VHF frequencies.

Conventional synthetic aperture focusing techniques usually make the assumption that focusing phase compensation can

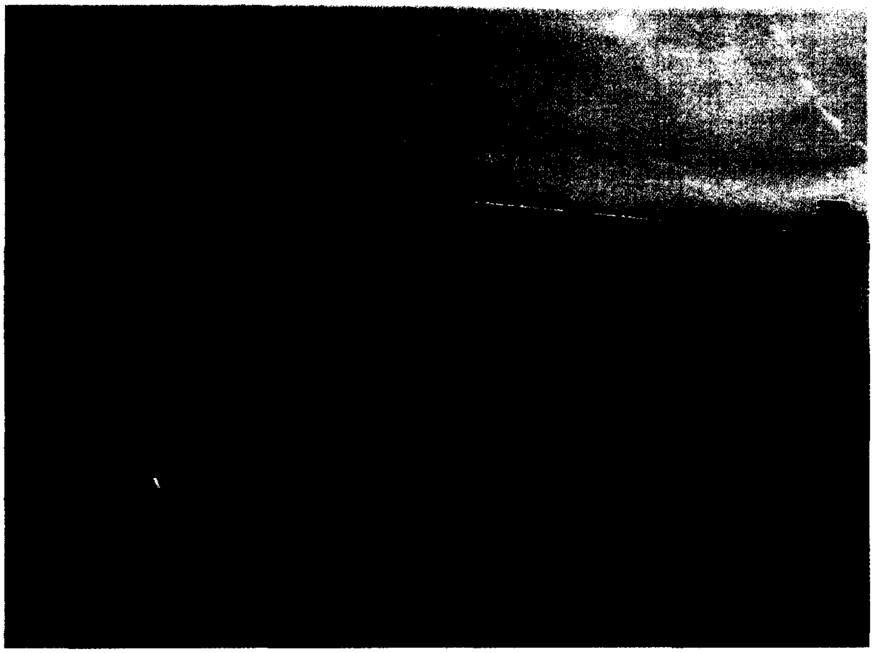

Figure 5: Tower-trailer with tower stowed

be made using the carrier frequency phase. This procedure will not work for the MOSS processor due to the large percent bandwidth used for data collection. To overcome this limitation, we perform the focusing completely in the frequency domain (see Figure 8). The receive data is Fourier transformed and near-field focusing phase compensation is performed by multiplying each frequency band by a phase factor exp[-2πift], where f is the carrier frequency corresponding to the Fourier transform frequency bin, and t is the round trip travel time from the antenna phase center to the center of volume cell (voxcell) being imaged. The calculation of the round trip travel includes ray bending effects to account for propagation within the soil, when subsurface voxcells are being imaged.

The accurate calculation of the round-trip travel time assumes that the antenna position is known to an accuracy better than 0.1 wavelengths. The measurement of antenna position in the field represents a practical challenge. To reduce the measurement requirements, a preliminary measurement is made. This measurement is subsequently refined by placing a phase locked transmitter in the scene and collecting calibration data from several transmitter locations. The antenna positions are then recovered by least squares fitting the transmitter phase over the entire aperture. The transmitter signature is also used to provide calibration curves for the system response over the processing band.

The RFI environment at UHF and VHF can present a significant challenge. We compensate for RFI contamination using a three-level scheme. For each transmit pulse, data of similar duration is collected before and after the transmission event. The complex Fourier transform of this data is examined and possible RFI contamination identified on a single pulse basis by identifying bins whose amplitude exceeds the value expected given the thermal and signal noise levels. A coherent estimate of the RFI contamination is made using the combined before and after calibration

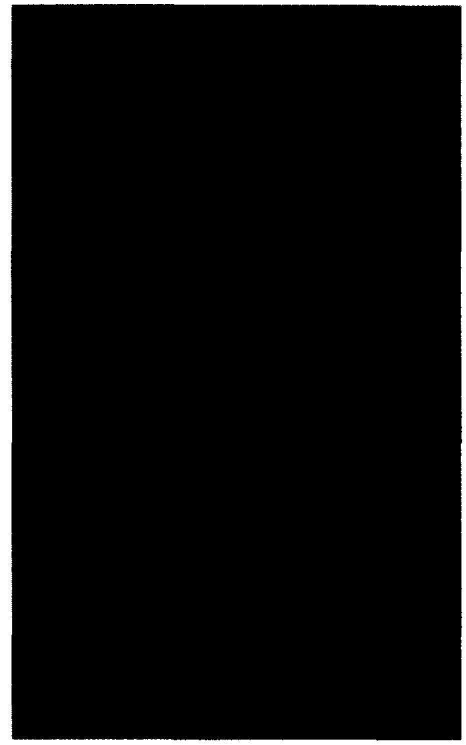

Figure 6: Retractable tower deployed

data, and the estimate is subtracted coherently from the received pulse spectrum. For this procedure to be valid, it is assumed that the RFI remain coherent over the single pulse and bracketing calibration times. Further reduction in RFI contamination is then obtained by coherently averaging the return and noise calibration signals over long times, compared to the RFI correlation times. Since the scene speckle is assumed to remain stationary, the resulting coherent gain will improve the signal to thermal and RFI noise ratios significantly. The average noise only calibration result is then used to generate a frequency dependent calibration curve which will be subtracted from the incoherently averaged cross section estimates.

The last step of the processing involves incoherently combining frequency bins to estimate the polarimetric Muller matrices and estimating the scattering cross section.

Ground Truth and Site Characteristics

The radar will record backscatter measurements at intervals in accordance with the ground-truth schedule. The result will be a comprehensive data set illustrating the temporal correlation and radar penetration effectiveness for moisture observations. We will provide *in situ* measurements of soil water content at various depth layers in a soil profile under different vegetation canopies. The vegetation canopies will be grassland, forest canopies, and an arid site, at locations in Oklahoma, Oregon, Manitoba and Arizona. The measurements will be nearly continuous in time, i.e. at 15 min or 30 min intervals and to a depths of about 1-2 m, depending on the site. The same radar equipment will be transported to various sites, the timing of which will be determined to optimize seasonal observations at each site. The first deployment of this radar is late 2002.

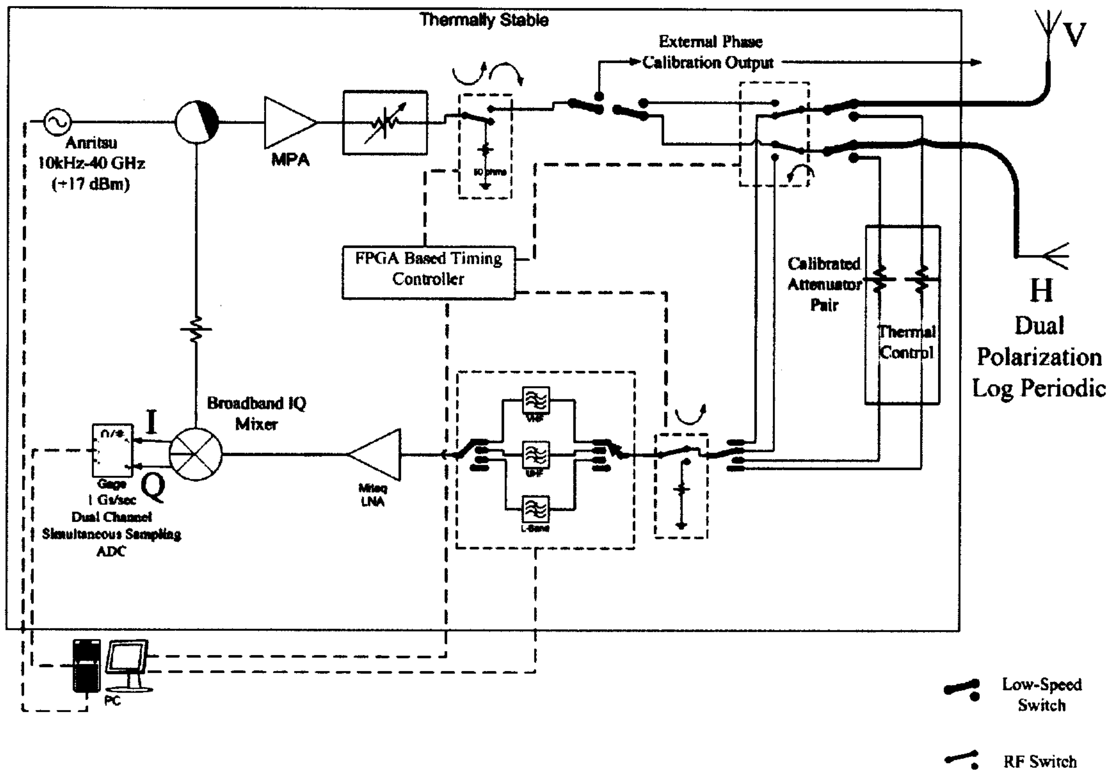

Figure 7: Tower-based radar system block diagram

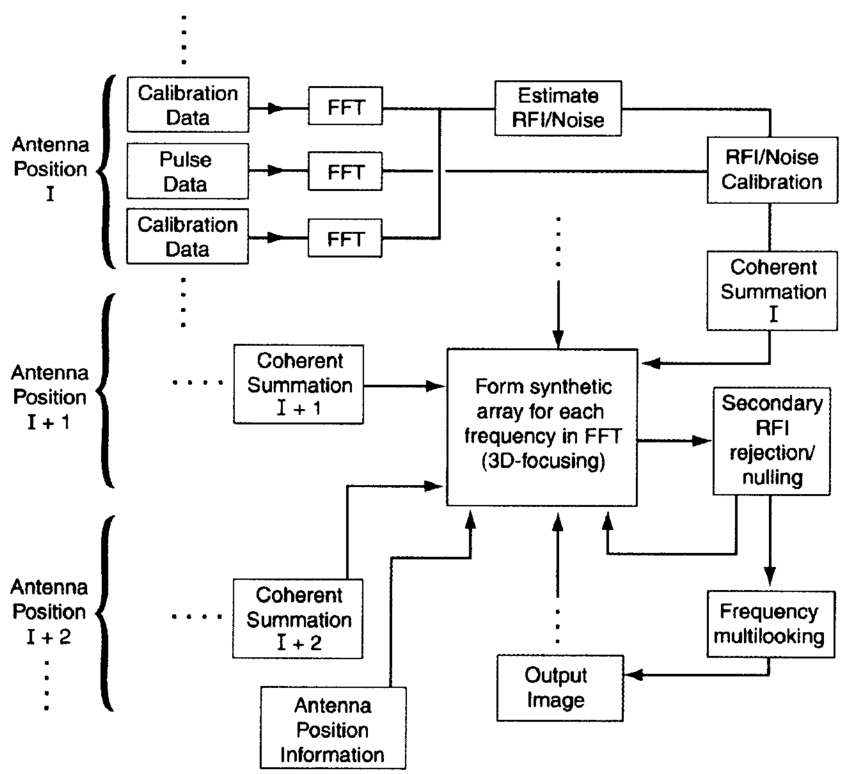

Figure 8: MOSS processor diagram for the tower prototype

5. Conclusions

The MOSS instrument set will allow the estimation of surface and at-depth soil moisture below canopies with densities that make them opaque in higher microwave frequencies. However, the MOSS program presents a number of unique system design challenges and issues. The large dual-frequency antenna, large swathwidth requirements and the low frequencies (at which ionspheric effects, RFI and frequency allocation become significant issues) combine to make this program particularly challenging. Furthermore, measurements such as these have never been made at VHF requiring a tower-based prototype to provide data for algorithmic development and verification.

To date a preliminary spaceborne design and performance analysis has been performed that indicates that the resolution and swathwidth requirements can be met while retaining reasonable transmit power levels, low data rates and acceptable azimuth ambiguity levels. We will continue to refine this design, particularly as a result of the tower-based ground experiments which will provide greater insight into the backscatter dependence and properties of these frequencies under different environmental conditions.

The tower-based prototype is designed and built. Although the radar design is reasonably straightforward, there are unique issues in fielding this instrument that necessitate a reasonably complex data-taking and processing procedure. We use a single antenna set mounted on a 45m tall tower to synthesize an aperture in two-dimensions over instrumented sites. The need to know the position of the antennas to 0.1 of a wavelength requires active calibration by a tone generator in the scene. RFI is minimized through coherent integration and the coherent gain improves the signal to thermal noise ratio. The data collected by this radar are unique in providing data products not obtained from any other existing instrument.

References

[1] Nichols, W. E., R. H. Cuenca, T. J. Schmugge and J. R. Wang. 1993. Pushbroom Microwave Radiometer Results from HAPEX-MOBILHY. *Remote Sensing of the Environment,* Vol. 46 (2), pp. 119-128.

[2] Jackson, T. J., D. M. Le Vine, A. Y. Hsu, A. Oldak, P. J. Starks, C. T. Swift, J. Isham, and M. Haken, 1999. Soil moisture mapping at regional scales using microwave radiometry: the Southern Great Plains hydrology experiment, *IEEE Transactions on Geoscience and Remote Sensing*, 37, 2136-2151.

[3] Jackson, T. J., and T. J. Schmugge, 1991. Vegetation effects on the microwave emission of soils, *Remote Sensing of the Environment*, 36, 203-212.

[4] Dobson, M. C., et al., 1992. Dependence of radar backscatter on conifer forest biomass. *IEEE Trans. Geosci. Remote Sensing*, vol. 30, pp. 412-415.

[5] Freeman, A., S. L. Durden, and R. Zimmermann, 1992. Mapping Subtropical Vegetation Using Multifrequency, Multipolarization SAR Data. *Proc. IGARSS'92*, Houston, TX, pp. 1986-1689.

[6] Rignot, E., R. Zimmermann, J. van Zyl, and R. Oren, 1995. Spaceborne applications of a P-band imaging Radar for mapping of forest biomass. *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 5, pp. 1162-1169.

[7] Moghaddam, M., S. Saatchi and R. H. Cuenca. 2000. Estimating Subcanopy Soil Moisture With Radar. *J. Geophys. Res.*, Vol. 105, No. D11, pp. 14,899-14,911.

[8] Dubois, P., J. van Zyl, and T. Engman, 1995. Measuring soil moisture with imaging Radars. *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 4, pp. 915-926.

[9] Oh, Y., K. Sarabandi, and F. T. Ulaby, 1992. An empirical model and an inversion technique for radar scattering from bare soil surfaces. *IEEE Trans. Geosci. Remote Sensing*, vol. 30, pp. 370—381.

[10] Freeman, A., S. L. Durden, and R. Zimmermann, 1992. Mapping Subtropical Vegetation Using Multifrequency, Multipolarization SAR Data. *Proc. IGARSS'92*, Houston, TX, pp. 1986-1689.

[11] Thomson, M., 1998. The Astromesh deployable reflector, *IUTAM IASS* Symposium on Deployable Structures: Theory and Applications, 6-9 September 1998, University of Cambridge, U.K

[12] Thomson, M., 1999. The Astromesh deployable reflector, *IMSC'99*, June 16-19, Ottawa, Canada.

[13] Huang, J, Y. Rahmat-Samii and M. Moghaddam, 2003., A VHF/UHF dual-band dual-polarized microstrip array, to be presented at *PIERS 2003*, Honolulu, Hawaii

[14] Tsang, L., J. Kong, R. Shin, Theory of Microwave Remote Sensing., New York: Wiley Interscience.

[15] Ishimaru, A., Wave Propagation and Scattering in Random Media., New York: IEEE Press.

[16] Ulaby, F, R. Moore and A. Fung, Microwave Remote Sensing: Active and Passive, Norwood, MA: Artech House, Vol. 2, pp. 492-494

Biographies

Delwyn Moller *received a Bachelor of Engineering degree (1990) and a Master of Engineering degree (1992) from the University of Auckland in New Zealand. In 1997 she then completed a Ph.D. in radar remote sensing at the University of Massachusetts. She joined the Jet Propulsion Laboratory in 1997 where she is a Member of Technical Staff in the Radar Science and Engineering Section. Her* *tasks in this position have included system engineering and performance evaluation on a number of projects including the Shuttle Radar Topography Mission (SRTM), data-acquisition system design and data analysis and processing for along-track interferometry. She is currently a Co-I on an Instrument Incubator Program for a Dual-frequency (UHF and VHF) radar with application to soil-moisture retrieval.*

***Ernesto Rodriguez** joined the Jet Propulsion Laboratory in 1985. He is currently the technical group supervisor of the interferometric, synthetic aperture radar phenomenology group.*

***Mahta Moghaddam** received the B.S. degree in 1986 from the University of Kansas, Lawrence, Kansas with highest distinction, and the M.S. and Ph.D. degrees in 1989 and 1991 respectively, from the University of Illinois at Urbana-Champaign, all in Electrical and Computer Engineering. Her graduate research involved the solution of electromagnetic forward and inverse scattering problems for complex media, with applications to subsurface radar and medical imaging.*

Since 1991, Dr. Moghaddam has been with the Radar Science and Engineering Section, Jet Propulsion Laboratory, California Institute of Technology in Pasadena, CA, where she has been primarily involved in developing algorithms for quantitative radar image analysis. Her research interests include wave scattering and propagation in random and inhomogeneous media and application of nonlinear inversion and estimation techniques to interpretation of multichannel remotely sensed data. Her research activities have also included data fusion by combining polarimetric and interferometric SAR data, as well as combining polarimetric SAR and optical remote sensing data for nonlinear estimation of vegetation and surface parameters from airborne and spaceborne platforms. She has been the Principal and Co-Investigator on several research projects, and has authored or coauthored over 70 journal and conference papers. Her other responsibilities have included being a systems engineer for the Cassini Radar, the JPL Science group Lead for the LightSAR project, and a science consultant to the JPL Team X (Advanced Mission Studies Team).

Her recent research activities focus on large-scale vegetation product development from SAR imagery, as well as development of technologies and concepts for low-frequency spaceborne radars for subcanopy and subsurfaceobservations.

Dr. Moghaddam is a senior member of IEEE, member of URSI Commission B, Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.

***James P. Hoffman** received the B.S. degree in electrical engineering from the State University of New York at Buffalo, in 1996, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1999 and 2001, respectively. In 2001, he joined the Advanced Radar Technology Group, at the Jet Propulsion Laboratory, Pasadena, CA. His technical interests include technology development for microwave remote sensing and the study of planetary atmospheres. Dr. Hoffman won first prize at the 2001 National Radio Science Meeting (URSI) Student Paper Competition and was awarded the Technical Paper Prize in the Science Applications International Corporations (SAIC) Georgia Tech Student Paper Competition.*

ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.